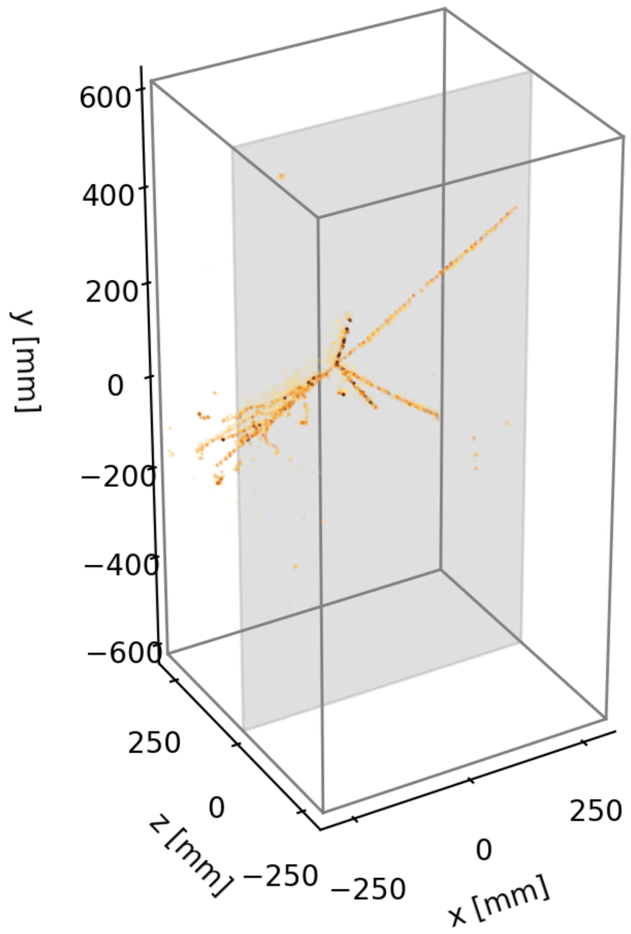
Pixel Instrumentation for Neutrino Detectors

Dan Dwyer

Snowmass Community Summer Study (Seattle)

23 July 2022

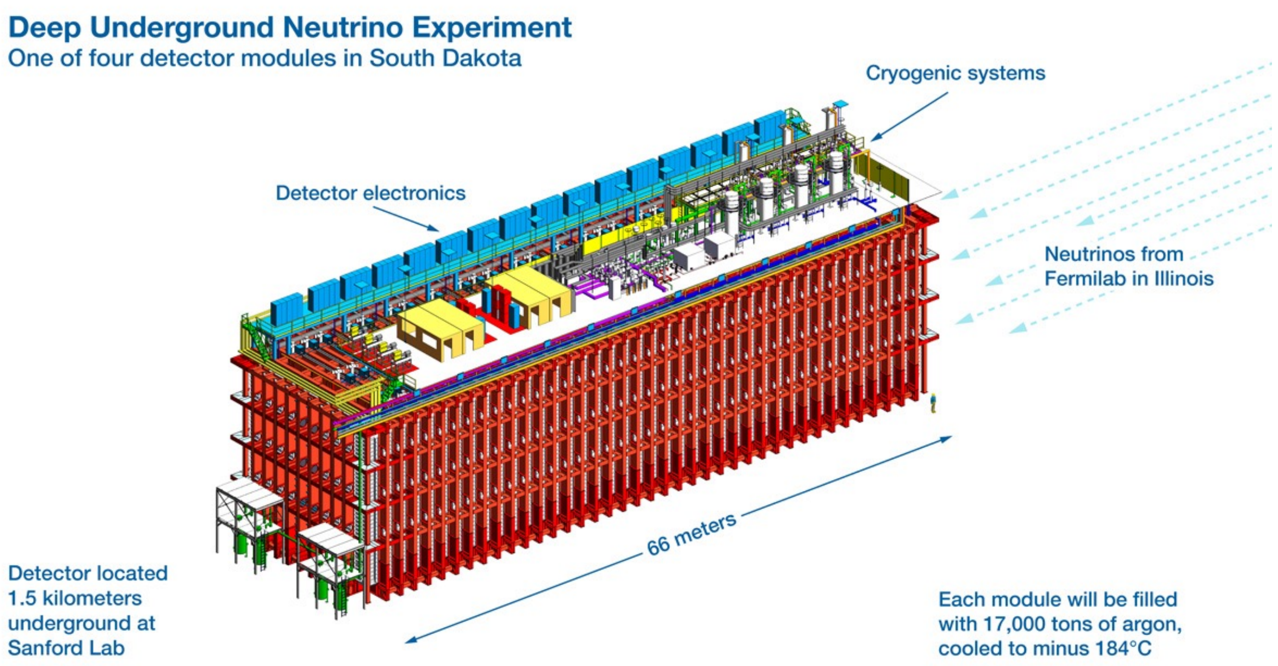


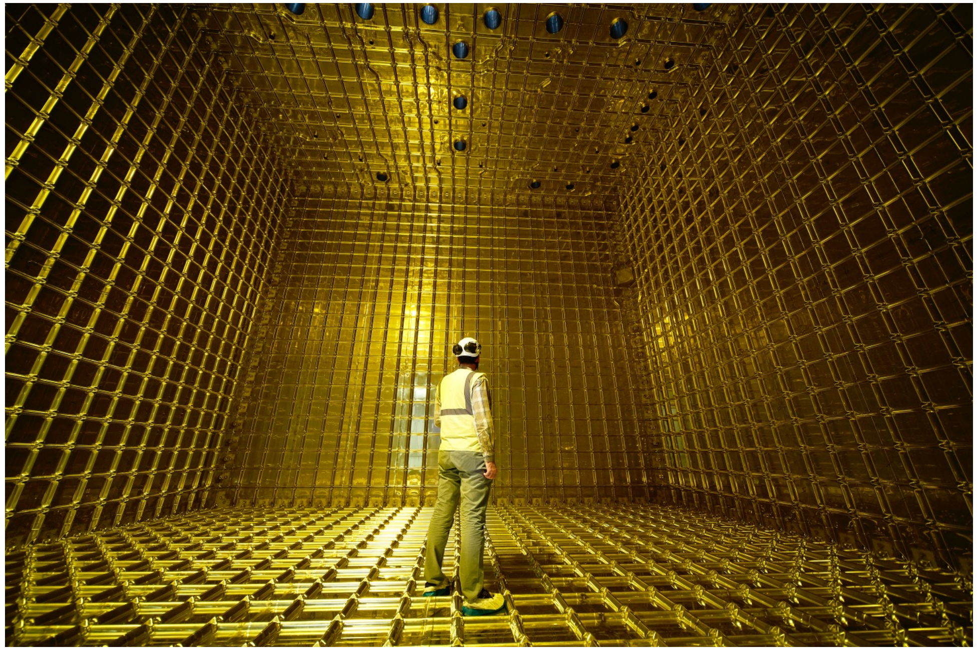
Neutrino Instrumentation Challenge

Deliver mm-scale spatial granularity for stadium-sized detectors.

Example: DUNE

- DUNE consists of four Far Detector modules, with a total volume on the order of **50,000 cubic meters**.
- To achieve the required precision, a **spatial granularity of ~4mm** is required over this volume.
- Corresponds to a detector with a total of **~1 trillion spatial voxels**.





DUNE prototype module ~1/200th of DUNE Module

Neutrino Pixels

Benefits:

- True 3D imaging
- 'Triggerless', 100% uptime

Science Gains:

- Improved signal fidelity, S/B
- Enhanced low-energy program

  [*JINST* **15** P04009](#)

  [arXiv:2203.12109](#)

Challenge:

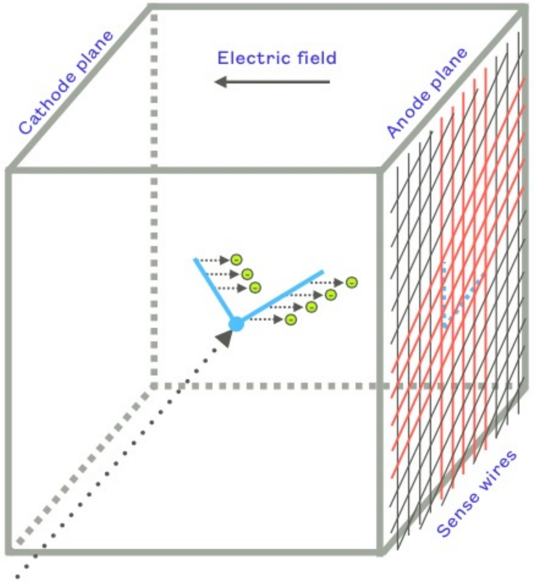
Very high channel counts

O(100k) channels/m²

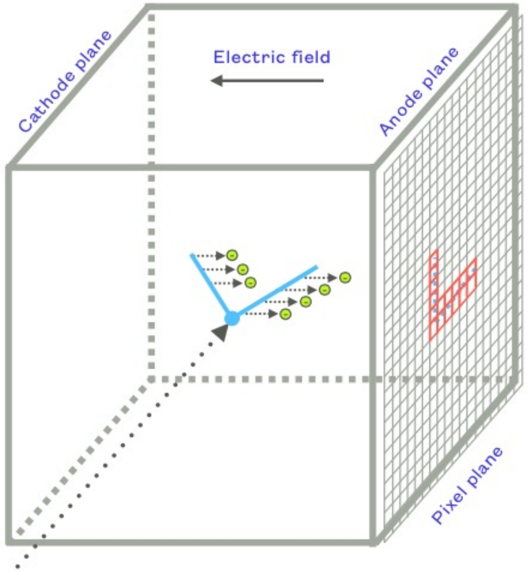
Requires:

- Very low power
- Minimal cabling
- Cryogenic robustness
- Scalable production

2D Projective TPC

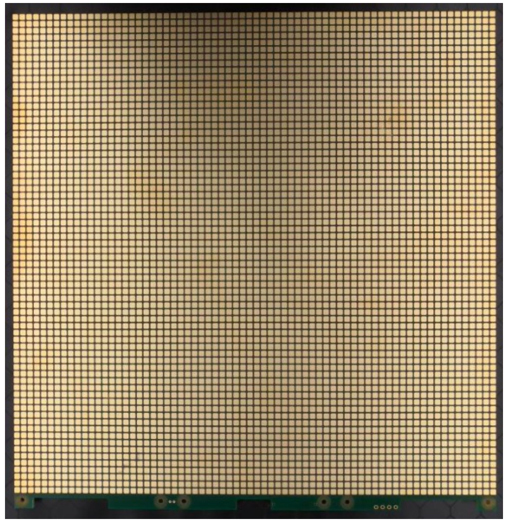


3D TPC

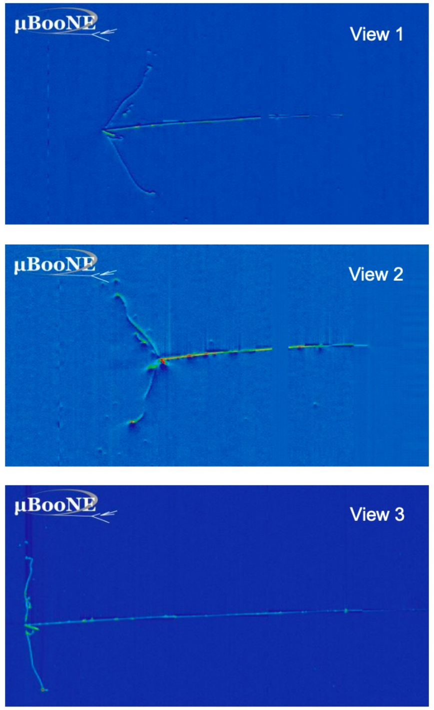


DUNE prototype anode plane on winding machine

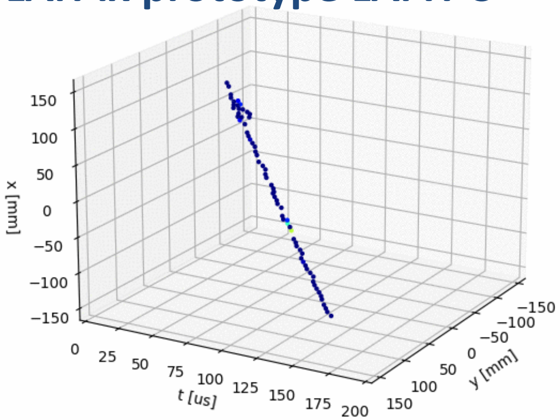
6.4k-channel LArPix prototype pixel anode tile



2D Projections in MicroBooNE



Raw 3D Cosmic Ray images in LArPix prototype LArTPC



LArPix

BERKELEY LAB

Berkeley
UNIVERSITY OF CALIFORNIA

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

UCDAVIS
UNIVERSITY OF CALIFORNIA

Caltech

UC SANTA BARBARA

b
UNIVERSITÄT
BERN

Penn

UCI University of California, Irvine

Yale

YORK
UNIVERSITÉ
UNIVERSITY

R&D on Feasibility: LArPix-v1 System

LArPix-v1: *2016-2018*

Complete 3D Pixel System for LArTPCs:
- Custom ASIC with amplifier, digitizer, multiplexer
- Integrated Pixelated Anode w/ASICs
- Control electronics and software (outside cryo)

Key R&D Achievement:
Demonstrated **technical feasibility**

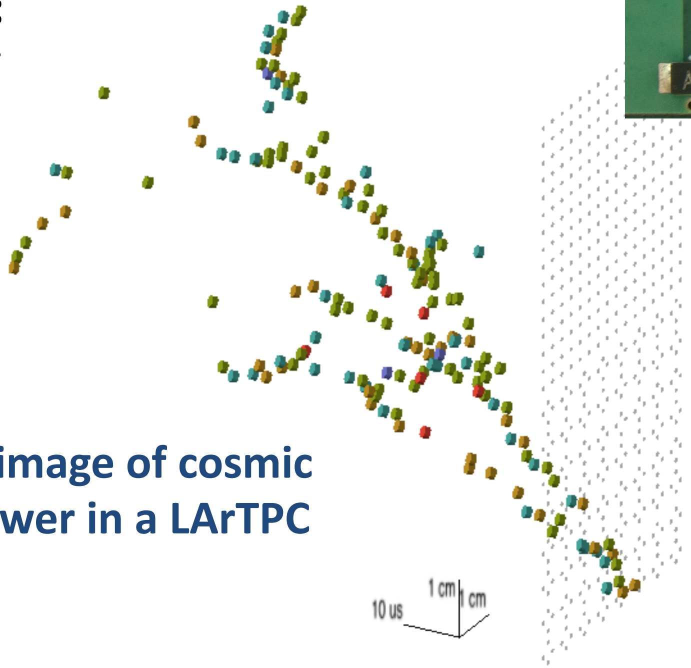
-> Successfully imaged cosmic rays in LArTPC

ASIC:
- Cryogenic-compatible
- Low-power: 62 uW/channel
- Low-noise: 275 e- ENC @ 87K

Pixel Anode:
- Cryogenic-compatible
- Low Digital-Analog cross-talk
- O(1k) channel readout via 2 wires

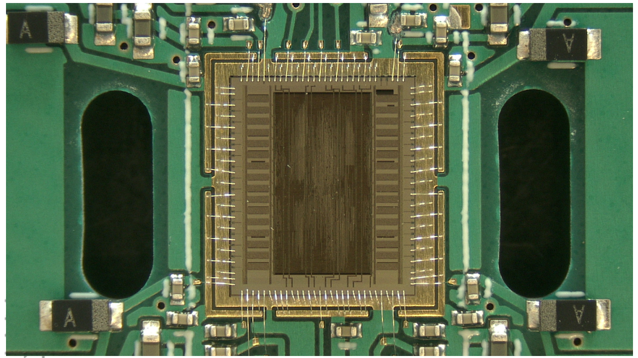
Control electronics:
- Fieldable system: noise-isolated and wifi accessible

Main drawback:
Difficult to scale above O(1k) pixels
- Anode requires manual assembly, bare chip wirebonding

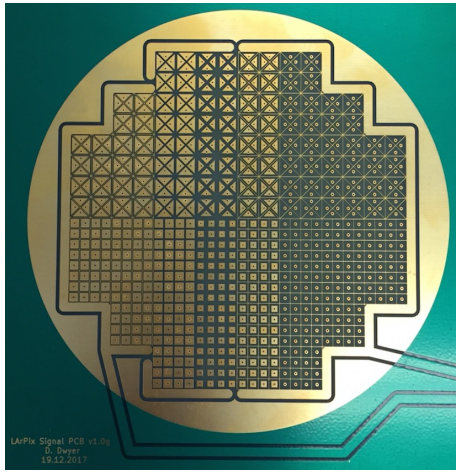


3D image of cosmic shower in a LArTPC

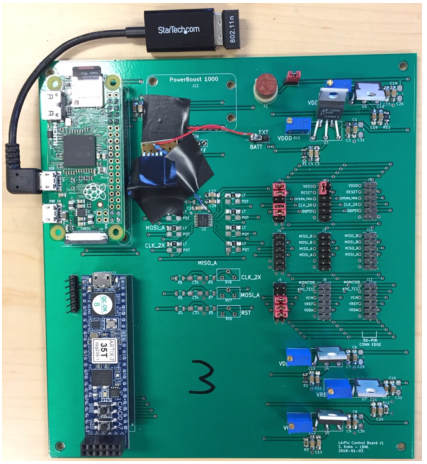
LArPix-v1 ASIC



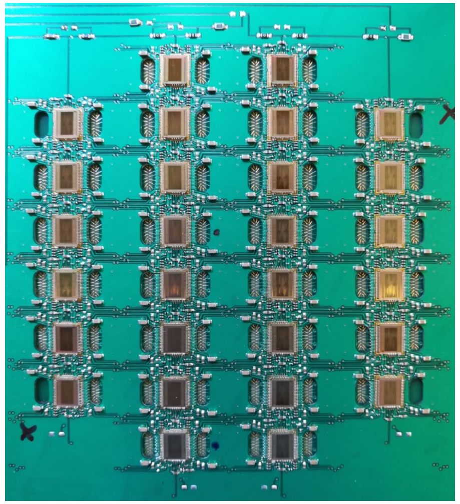
v1 Pixel Anode, Front



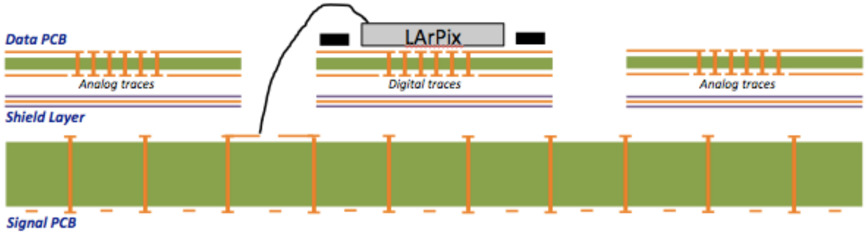
LArPix-v1 Tile Controller



v1 Pixel Anode, Back



Multi-layer anode cross-section



JINST 13 (2018) P10007

R&D on Scalability: LArPix-v2 System

LArPix-v2: *2019-2021*

Substantial Design Evolution:

ASIC Improvements:
- 64 channels/ASIC (twice channel density of v1)
- Hydra-I/O: Dynamic routing, robust to chip failure
- Cryogenic-compatible custom SRAM memory
- Improved tunability, testability
- Packaged to facilitate commercial mass production

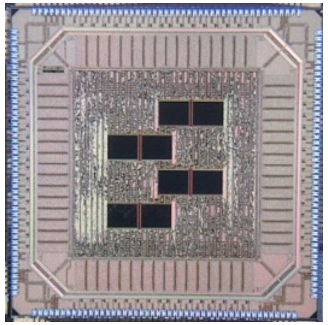
Pixel Anode Design Overhaul:
- 'Tileable' design to cover anodes of arbitrary scale
- 32cm by 32cm pixel anode PCB tile
- Frontside: 4900 square pixels, 4.4 mm spacing
- Backside: 10x10 grid of ASICs
- Enable fully-commercial mass production and assembly

Warm Controller (PACMAN) Redesign:
- Noise-isolated, compact, flange-mounted

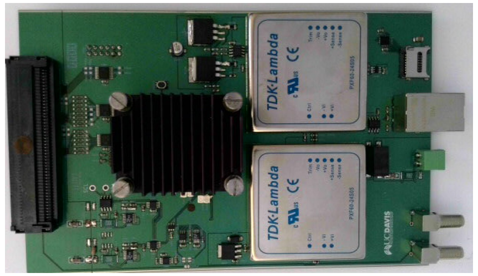
Key R&D Achievement:

Demonstrated **robust and scalable pixel anode**
- Fast (~few weeks) fully-commercial production/assembly
- Robust to repeated cryogenic cycling
- Successfully imaged cosmic rays in LArTPC on first try

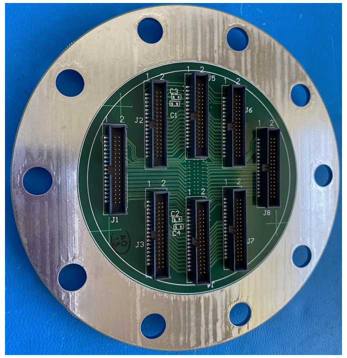
LArPix-v2 ASIC



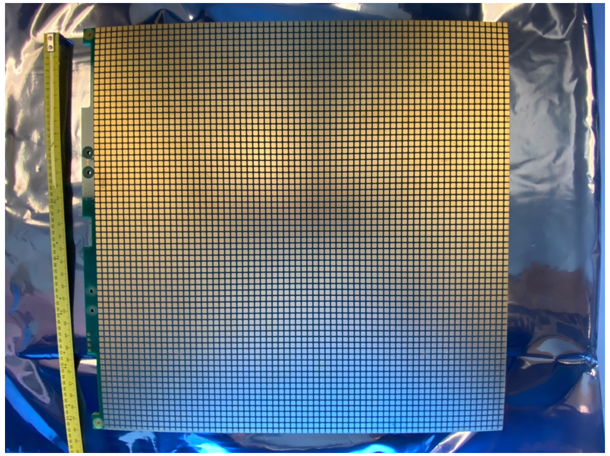
PACMAN Tile Controller

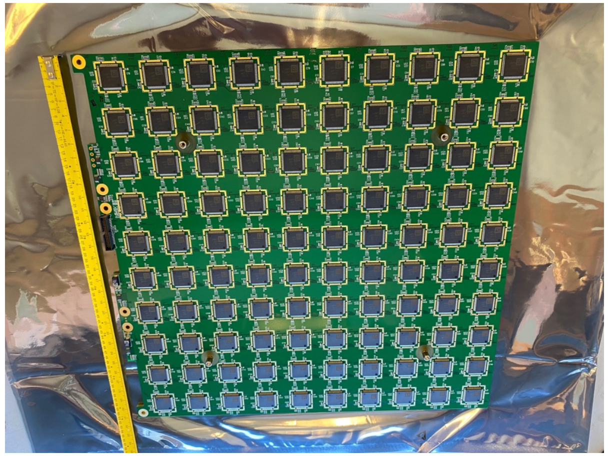


8-Tile Feedthrough

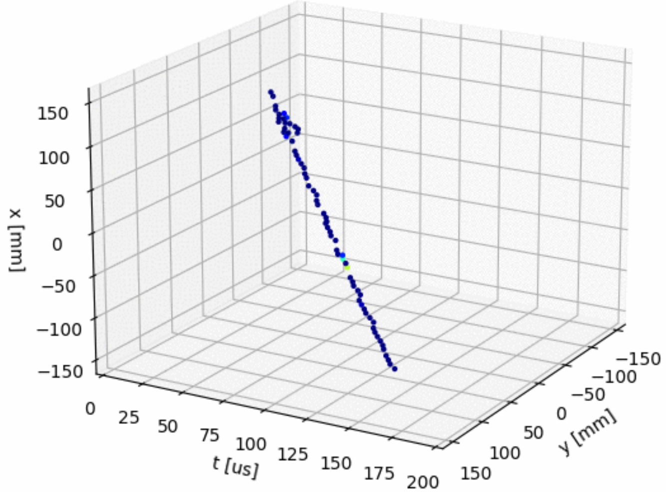


Production-scale LArPix-v2 Pixel Anode





Raw 3D images of cosmic rays from initial single-tile test



"LArPix-v2: a commercially scalable large-format 3D charge-readout scheme for LArTPCs" publication in preparation

Prototyping: ArgonCube 2x2 LArTPCs

Four ton-scale Prototype TPC Modules to validate DUNE Near Detector Design

Each TPC Module:

- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with ~80k pixel channels total
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

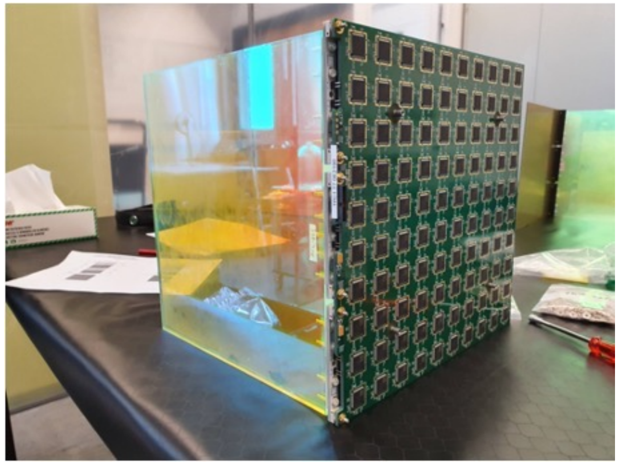
Progress @ Univ. of Bern:

- TPC Module 0:
  Run 1 (Demonstration): *Apr. 1-10, 2021*
  Run 2 (Extra Cryo-test): *Jun. 21-26, 2021*
- TPC Module 1 Operation:
  Feb. 5-13, 2022

Achievements:

Demonstrated fully-integrated prototype detector module at a scale relevant to the DUNE Near Detector

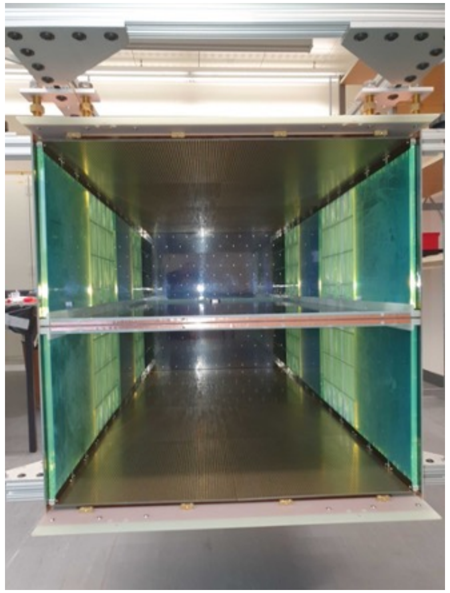
Single pixel tile & light module assembly



LArTPC module attached to cryostat lid

One anode, fully-assembled

Two anodes, installed inside field cage



Single Module Cryostat

LArTPC inside cryostat

Prototyping: ArgonCube 2x2 LArTPCs

*Typical **raw data** from cosmic ray interactions imaged in 3D prototype detectors*

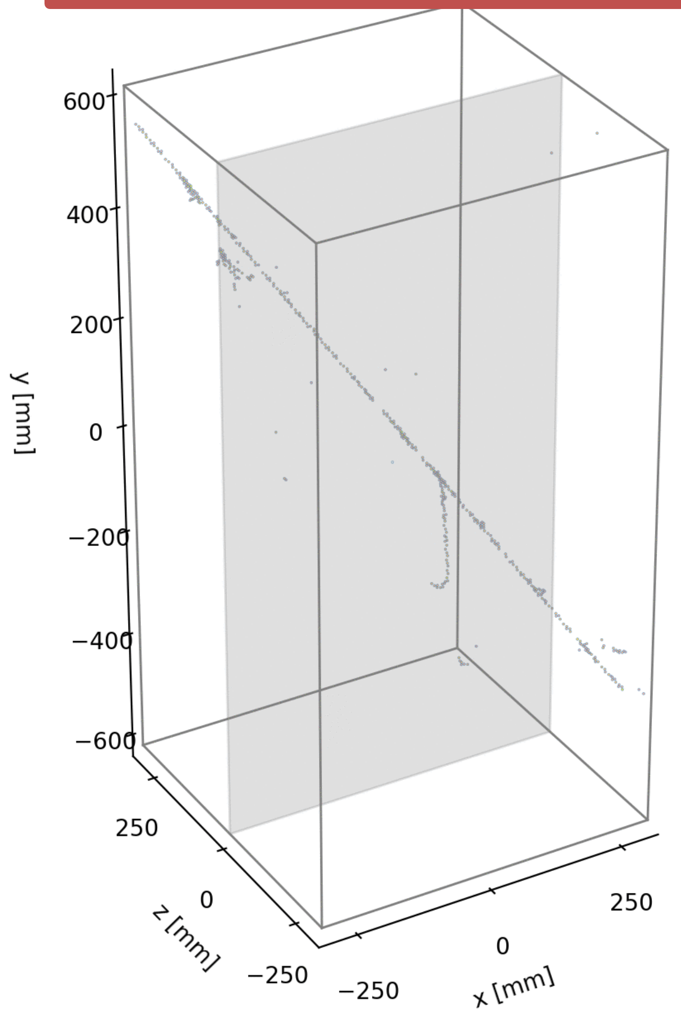
Verified design meets technical requirements:

- Collected >10^7 cosmic ray events
- Stable **HV** at ~30kV (~1 kV/cm drift, 2x target)
- Stable **Purity** at >2ms (>4x target)
- MIP Charge Signal-to-**Noise** >20:1 (at target)

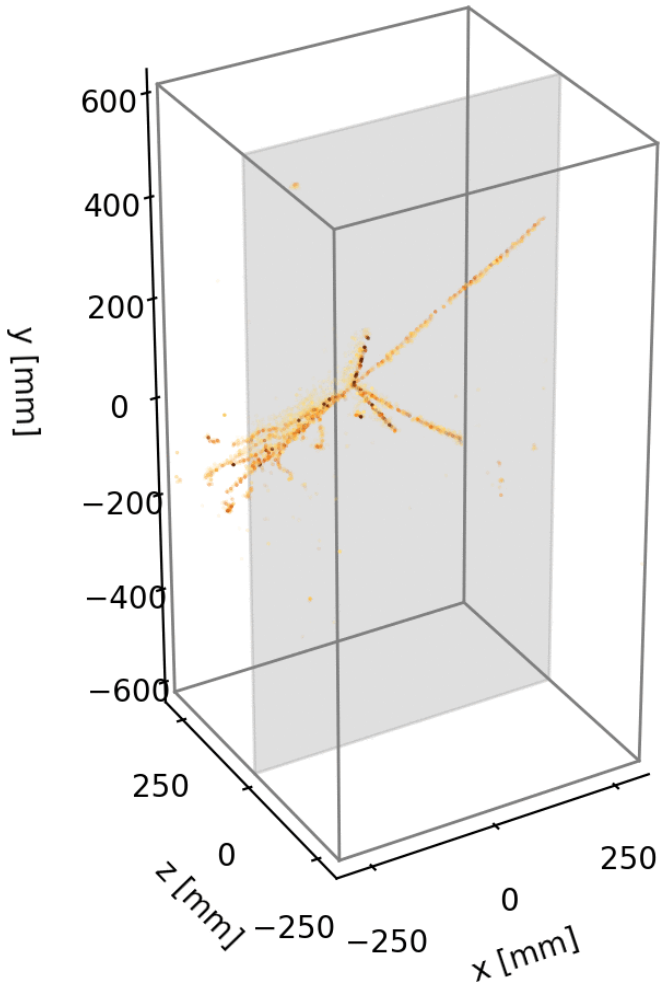
Continuous readout:

~100% live, independent of light system
Low data rate due to self-triggered design

Arguably the most performant ton-scale LArTPC to date.



Module 0 LArTPC

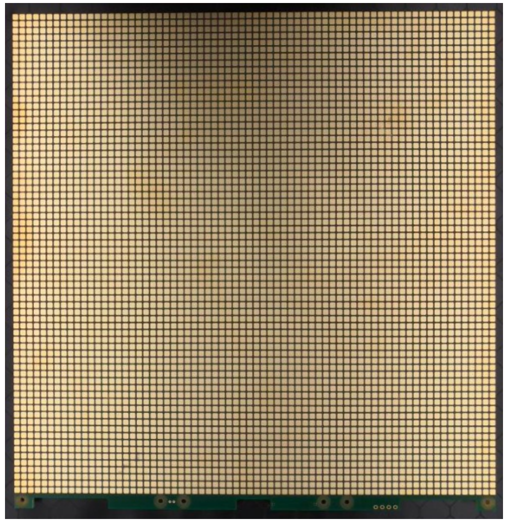


Module 1 LArTPC

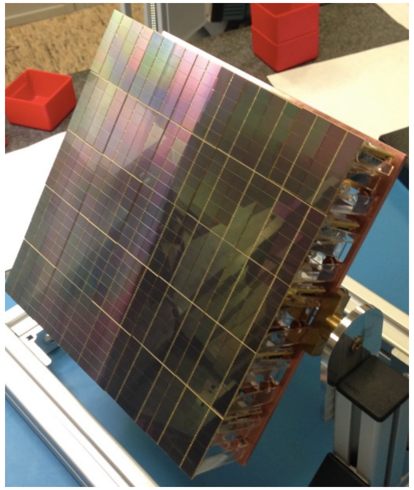
LightPix: Scalable Cryogenic SiPM Readout Electronics

- **Readout Electronics Needs:**
  - Low-power cryogenic-compatible scalable SiPM readout electronics at very low system cost
- **R&D Plan:**
  - **LightPix:**
    - Adapt existing LArPix ASIC to provide scalable readout for many (e.g. $>10^6$) Silicon Photomultipliers
    - Reuse all of LArPix system architecture (low-power, cryo-compatible, scalable, O($0.10)/channel system cost)
    - Provide a path for highly-granular photodetection systems for very large detectors

***Rough concept:** Replace LArPix charge-collection pixels with SiPMs*



e.g. Prototype 6.4k-channel LArPix-v2 tile



e.g. Darkside-20k prototype light sensor

Why LightPix:
Existing readout electronics are either too high power or too high cost for our cryogenic detector needs.

Looking ahead:
Personally, I think LightPix fits some specific near-term HEP needs (next 5yrs). In the long-term (5-10yrs), my guess is that digitally-integrated SiPMs may eventually provide better performance at lower cost.

LightPix ASIC

LightPix-v1:

- Develop and test dedicated time-to-digital converter (TDC) to provide < 10ns time resolution
- Add multi-channel coincidence triggering mode to suppress excess data from dark noise at room temp

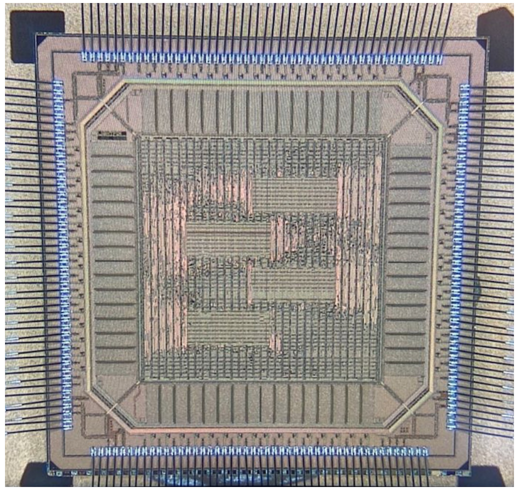
Progress:

- Received Aug. 2021
- Power-up, configuration successful
- TDC meets design targets

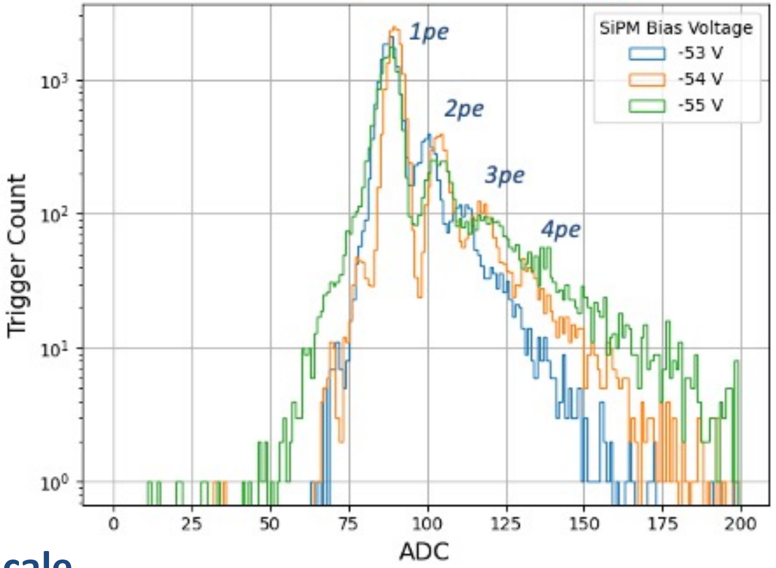
Next Steps:

- LightPix-v2:
  Provide both TDC and ADC functionality
- Deployment and testing of light detector system in prototype LArTPC
- Exploration/optimization of light detector formats

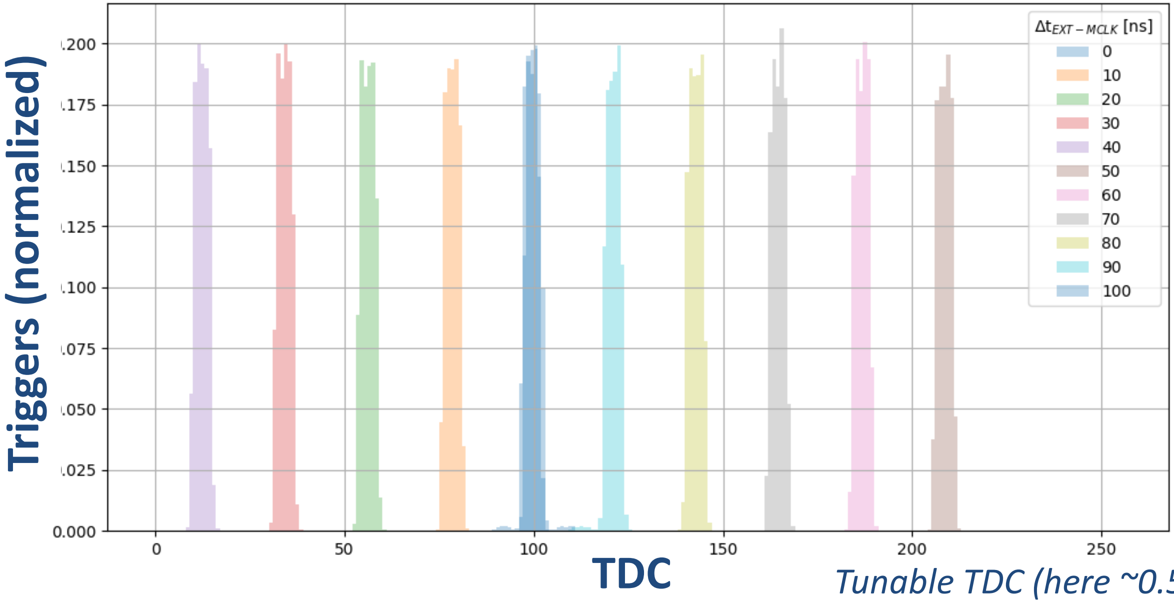
LightPix-v1b ASIC



Photoelectron signal spectrum vs. SiPM bias



Very-low-power TDC achieves ~ns-scale precision in response to external pulse



Offset between external pulse and TDC stop signal

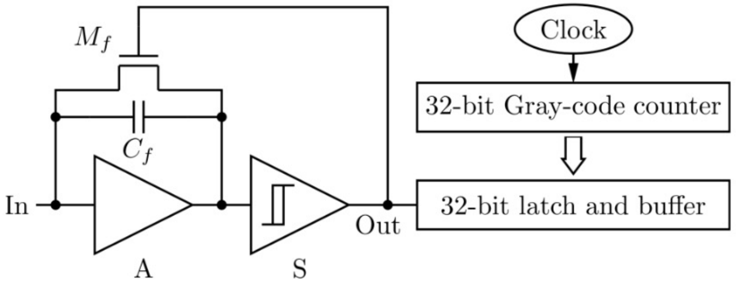
Tunable TDC (here ~0.5ns/tick)

QPix

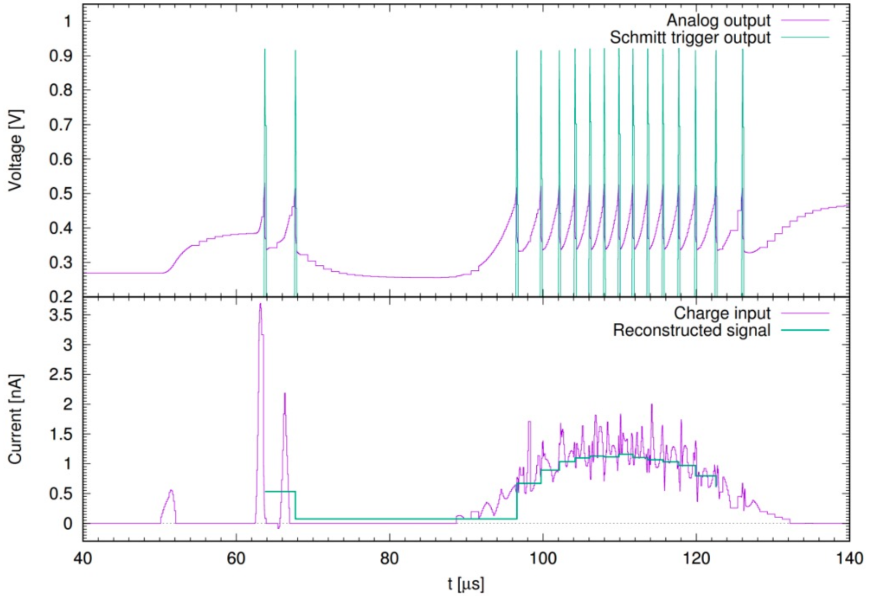
QPix: Concept and Progress

Concept: arXiv:1809.10213

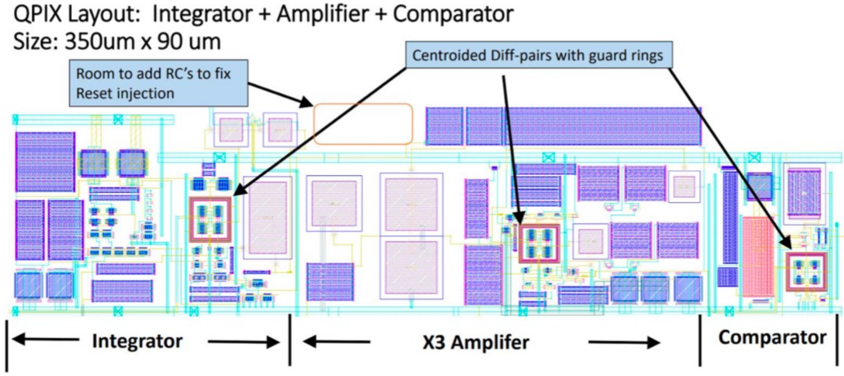
Report ‘time between resets’ instead of digitizing charge



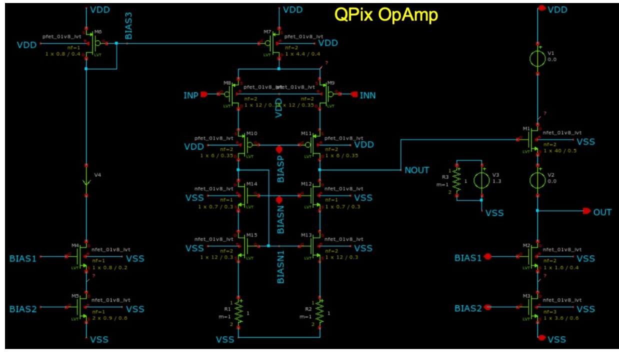
Distribution of reset times proxy for signal current on pixel



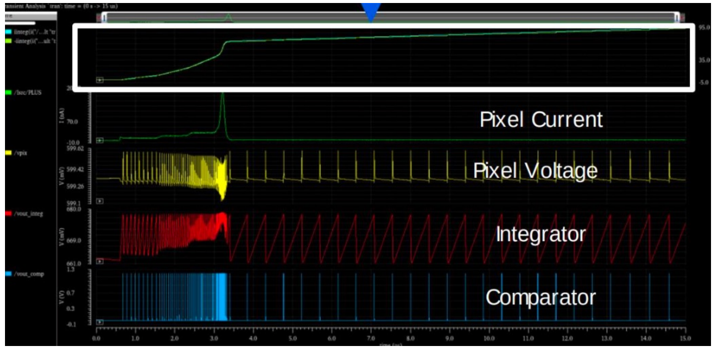
Front-end Prototype ASIC
(180nm, UPenn)



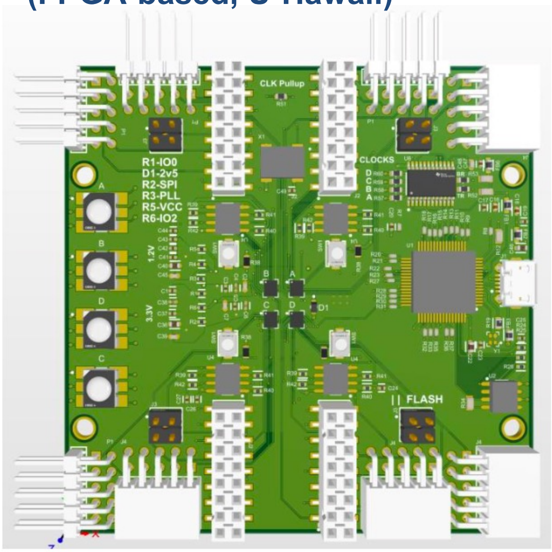
Front-end Prototype ASIC
(130nm, UTA)



Front-end Design
(65nm, FNAL)



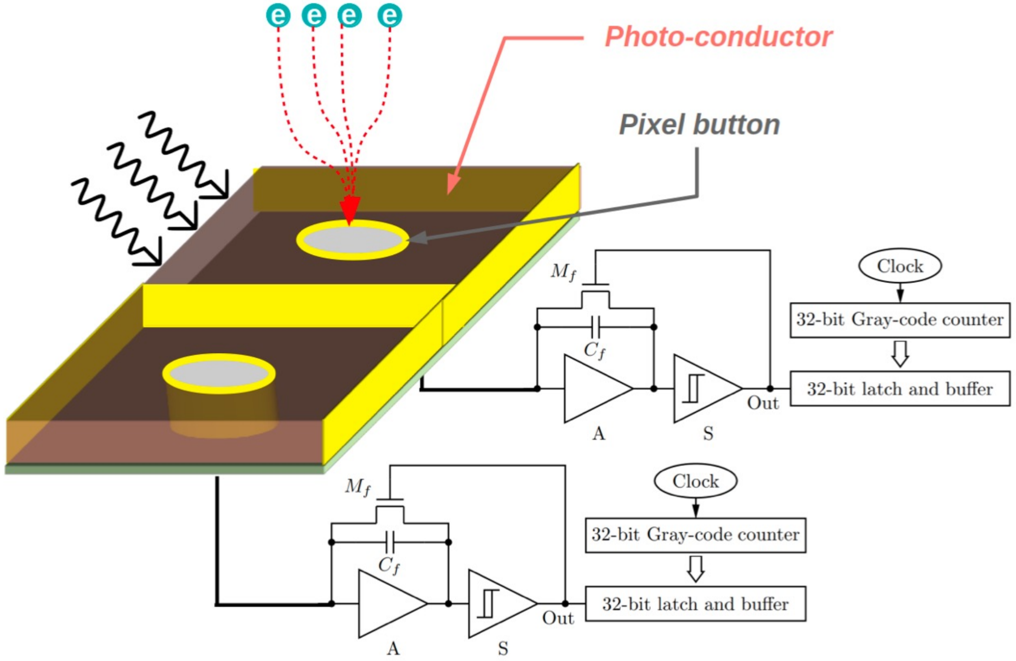
Digital Back-end Prototype
(FPGA-based, U-Hawaii)



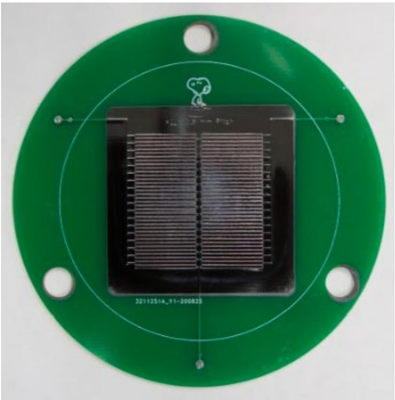
QPix: Light-sensitive Pixels

Concept:

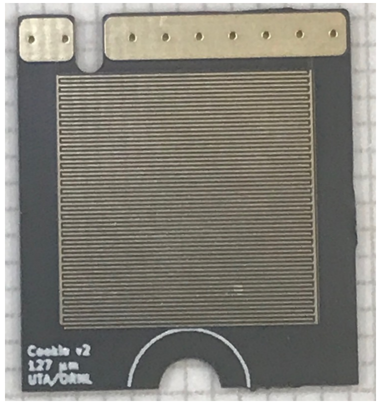
Add photoconductive (ASe) film to pixel anode to make pixels sensitive to both TPC charge and scintillation light



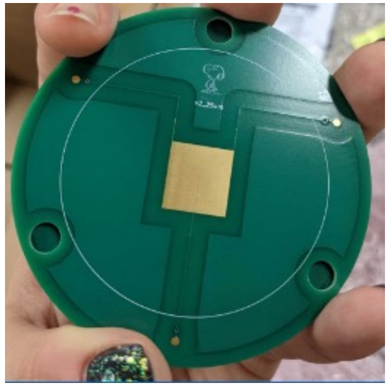
Prototype PCBs with biased traces coated in ASe



127 um trace spacing
5V/um max field
UTA/ORNL

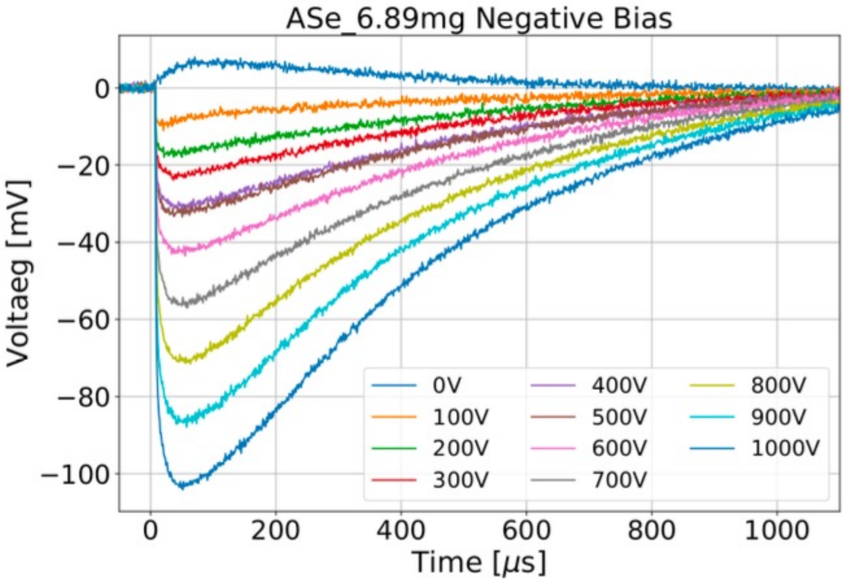


127 um trace spacing
5V/um max field
UTA/ORNL



25 um trace spacing
40V/um max field
UCSC/UTA/FNAL

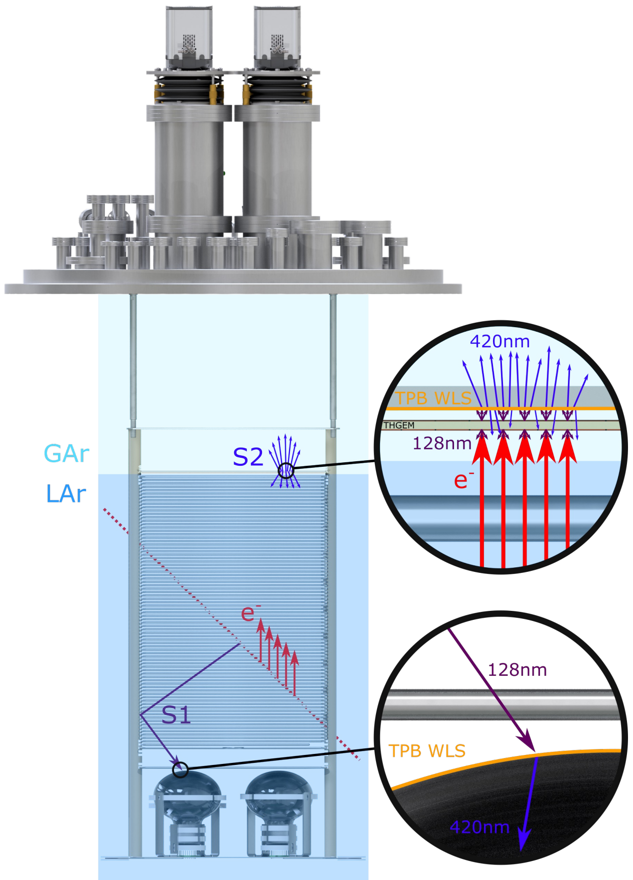
Example signal traces in response to light pulses



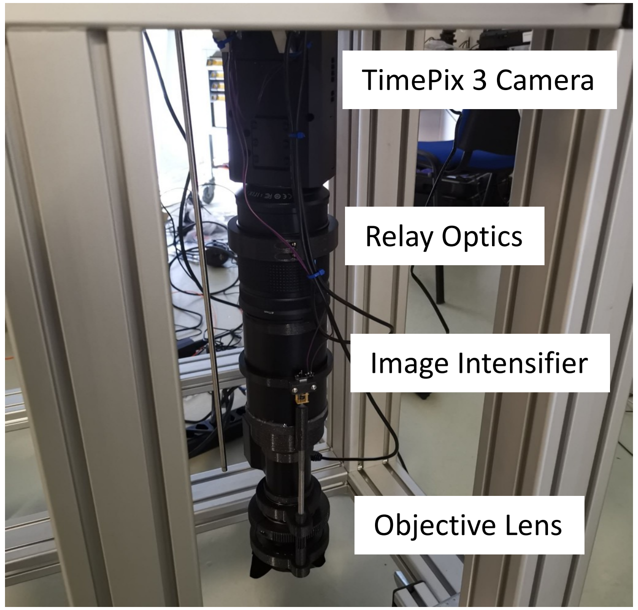
ARIADNE+

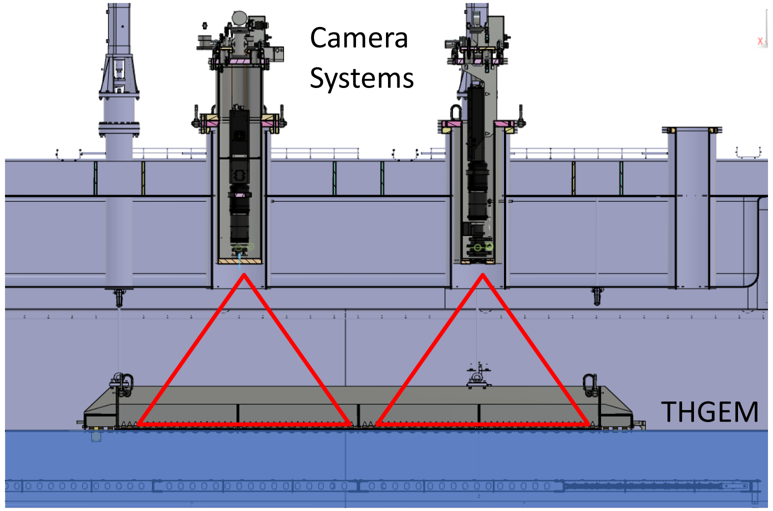
Concept:

Achieve Dual-phase TPC 3D readout by imaging electroluminescence in THGEM with fast optical cameras



Camera System





Advantages:

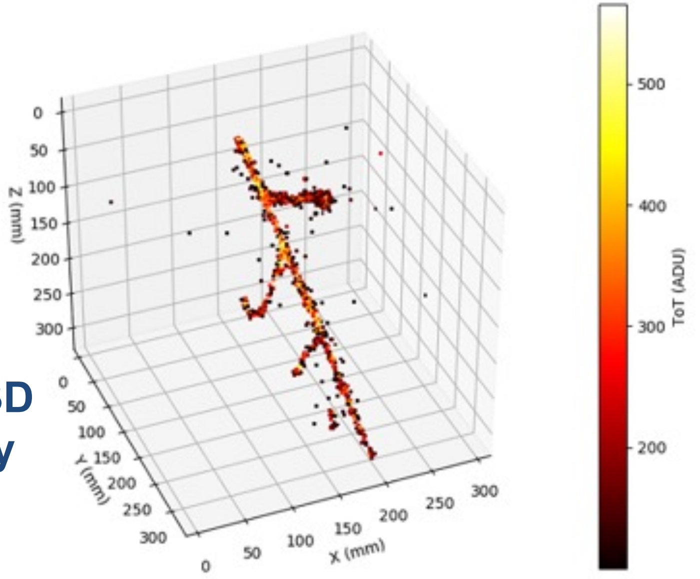
Low noise via optical-only readout
Low threshold due to gas amplification
Accessible/upgradeable: Cameras outside cryostat

Disadvantages:

Only viable in a dual-phase TPC
- High cathode voltage
- High-field e- extraction region
- THGEM amplification

Scattered/indirect light

Example 3D cosmic ray imaged in prototype



SNOWMASS21-IF7_IF8-NF10_NF0-UF3_UF0_Dan_Dwyer-171.pdf

R&D Collaboration

Snowmass LOI:

"Continued development of scalable pixelated detector systems could benefit from **a structured method for supporting detector R&D collaborations within the US DOE system.** Such an approach can be seen in the CERN RD Collaborations, which have been essential for delivering the technologies used by the current generation of large high-energy physics experiments."

e.g. RD-50 (Rad-hard semiconductors), RD-52 (MPGDs), RD-53 (Pixel Tracker ICs)

"The DOE, through the national laboratories, could provide a similar **shared infrastructure for supporting these R&D collaborations amongst a large number of university and laboratory partners.**"

"The **scalable pixelated detector R&D** proposed here **could serve as a test case for this model within the US.**"

Potential Future R&D:

- Finer detector granularity
- Embedded detector logic
- Increased system reliability
- Advances in commercial mass production.
- Adaptations:
  . Higher-bandwith detector systems
  . Adaptable readout logic
  . Large-area photodetection.

Snowmass2021 Letter of Interest: An R&D Collaboration for Scalable Pixelated Detector Systems

D. A. Dwyer[1], J. Asaadi[2], M. Garcia-Sciveres[1], C. Grace[1], A. Karcher[1], C. J. Lin[1], K. B. Luk[1,3], X. Luo[4], P. Madigan[1,3], A. Mastbaum[5], C. Mauger[6], M. Mooney[7], L. Mualem[8], M. Mulhearn[9], M. Newcomer[6], J. P. Ochoa-Ricoux[10], R. B. Patterson[8], B. Russell[1], S. R. Soleti[1], H. Steiner[1,3], Y.-T. Tsai[11], Z. Vallari[8], and R. Van Berg[6]

[1] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA*
[2] *Department of Physics, University of Texas at Arlington, Arlington, TX 76019 USA*
[3] *Department of Physics, University of California Berkeley, Berkeley, CA 94720 USA*
[4] *Department of Physics, University of California Santa Barbara, Santa Barbara, CA 93106 USA*
[5] *Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854 USA*
[6] *Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104 USA*
[7] *Department of Physics, Colorado State University, Fort Collins, CO 80523 USA*
[8] *Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125 USA*
[9] *Department of Physics and Astronomy, University of California Davis, Davis, CA 95616 USA*
[10] *Department of Physics and Astronomy, University of California Irvine, Irvine, CA 92697 USA*
[11] *Fundamental Physics Division, SLAC National Accelerator Laboratory, Menlo Park, CA 94025 USA*

August 31, 2020

Thematic Areas:
IF7: Electronics/ASICs
IF8: Noble Elements
IF9: Instrumentation Science: Cross Cutting and Systems Integration
NF10: Neutrino Detectors
UF03: Underground Detectors

Contact Information: Dan Dwyer (LBNL) dadwyer@lbl.gov

Introduction

Frontier experiments in neutrino and dark matter physics typically rely on large detectors, in the ton to many kiloton regimes. Achieving high-granularity readout in detectors at these scales requires new techniques in instrumentation design and production. Specific areas of development are large-area low-noise mixed-signal detector anode designs, system reliablity in the billion-channel regime, scalable and robust I/O architectures, and leveraging commercial methods for mass production. Recent advances in pixelated readout for large liquid argon time-projection chambers (LArTPCs) provide a concrete example of progress in this field [1, 2]. However, much development is still needed, and as the scale of that development necessarily increases, so do the required resources. Establishing a mechanism for coordinated R&D in this area that allows pooling of resources, similar to the CERN RD Collaboration model, would enable the required scale to meet the needs of future experiments.

Summary: Neutrino Pixels

LArPix:

- True 3D pixelated charge readout for LArTPCs
- Low-noise, low-power, cryogenic-compatible
- Self-triggering, 100% live
- Scalable anode design leverages commercial production
- Two recent 80k-pixel ton-scale prototype exceeded expectations
- Baseline technology for the DUNE Near Detector

LightPix:

- Highly-scalable readout for cryogenic SiPMs
- Reuses much of LArPix system design

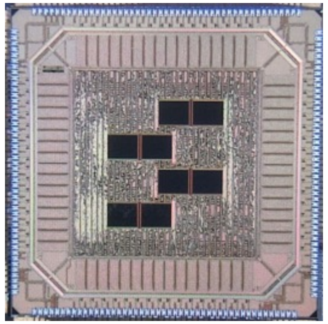
QPix:

- Record trigger time distribution instead of digitizing charge
- R&D on ASe coating to make pixels light-sensitive

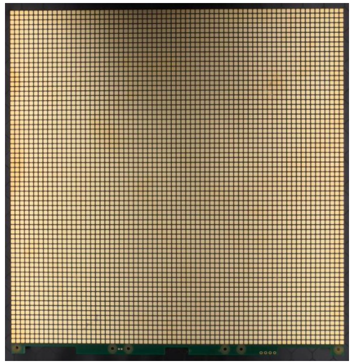
ARIADNE+:

- Optical 3D readout for dual-phase TPCs
- Successful mid-scale prototyping at CERN

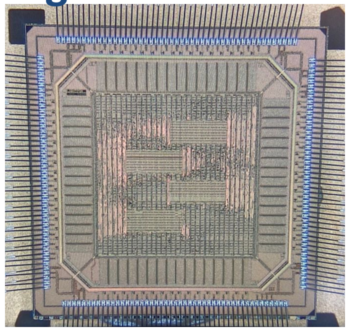
LArPix-v2 ASIC



LArPix-v2 Tile

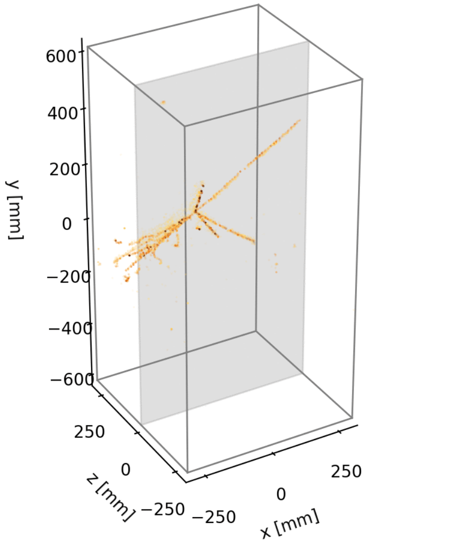


LIghtPix-v1 ASIC

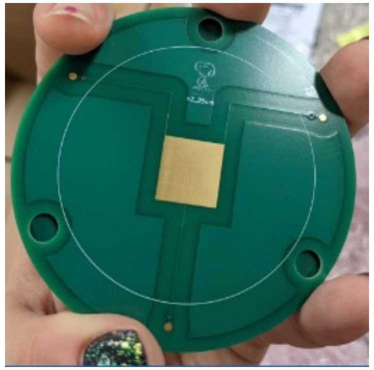


DUNE Near Detector Prototype LArTPC

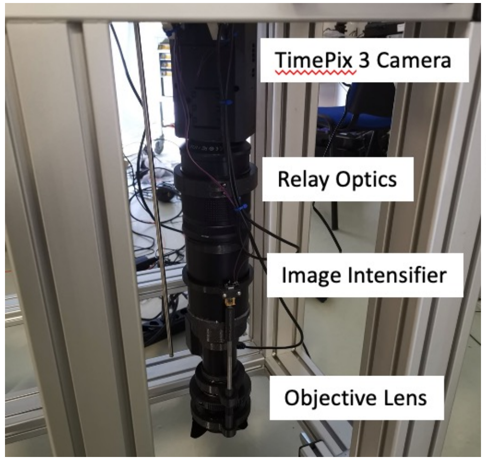
Cosmic ray 3D images from prototype

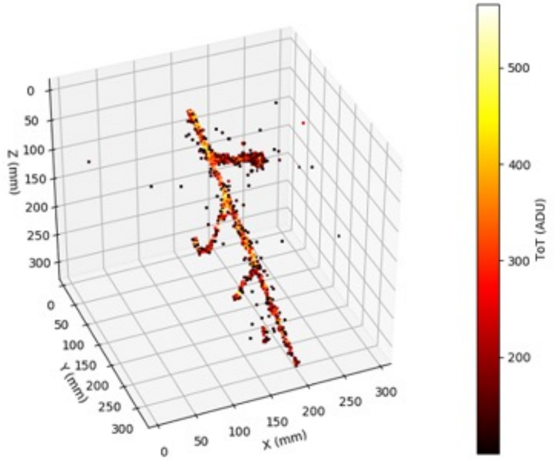


QPix ASe prototype



ARIADNE+ Camera System and 3D imaging





Potential technologies for future highly-granular detectors